Plenary Session

Silicon Carbide Technology in New Era
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Characterization and Defects in SiC
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Opportunities and Technical Strategies for SiC
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MoA2-1
(Invited)

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Owing to the significant progress in the growth of large and high-quality silicon carbide (SiC) bulk crystals without polytype mixing by sublimation above 2000°C and high-quality epitaxial layers on off-axis SiC(0001) at rather low temperatures around 1500°C, various types of SiC devices have been reported. Nowadays, 3-inch wafers of 6H- and 4H-SiC are commercially available, and Schottky diodes using the epitaxial layers have been delivered in the real semiconductor world.

Although many outstanding potentials of SiC have been demonstrated in various prototype devices projected for high-power, high-frequency, and high-temperature electronic devices including Schottky diodes, there are still many issues in technology for advanced SiC electronics. At the beginning of new era, a review on present-day SiC technology is necessary. Problems in bulk crystal growth, epitaxial growth, processes, and devices are briefly discussed.

Among them, the author raises the low-channel mobility in 4H-SiC MOSFETs, and introduces a trial to improve it. 4H-SiC has been regarded as the most promising polytype owing to its higher bulk mobility and smaller anisotropy than 6H-SiC. However, inversion-type MOSFETs fabricated on off-axis 4H-SiC(0001) wafers generally show an unacceptably low channel mobility, typically below $10cm^2/Vs$, which severely increases the on-resistance of SiC power MOSFETs. There have been several trials to improve the low channel mobility, either by annealing after device fabrication or to use a buried channel. Although the values of channel mobility have been improved actually, there would be barriers to use such processes or structures.

The author's group has proposed to use (11-20) at the last ICSCRM. A remarkable improvement in the values of mobility was shown together with the negative temperature dependence. The author reviews successful homoepitaxy on (11-20) and the inversion-type planar MOSFET performance. The origin of the high channel mobility on (11-20) substrates, which has been made clear after the last ICSCRM, is discussed based on the detailed analysis. In addition, other superior properties of (11-20) for the power devices will be reported.

Characterization and Defects in SiC

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SiC is a material of increasing interest for high power and high frequency applications. The material quality including understanding and control of defects is currently a limiting factor for many of the device applications. We have during the last years combined growth development of both epitaxial layers and bulk substrates, with a strong activity on defects and characterization. In this paper we will present suitable characterization techniques and recent results regarding important defects in epitaxial and semi-insulating bulk 4H SiC. This will include point and extended defects, defects created by irradiation techniques and finally defects created during processing or device operation.

One of the most important and most studied defects in SiC is the so called D1. This is an intrinsic defect always present after different particle irradiation and are formed after temperature annealing, and are then temperature stable. The defect can also be seen in as-grown material. The D1 is observed as an sharp BE at lower temperatures, and was recently correlated to the electrically observed hole trap HS1 seen in minority carrier transient spectroscopy (MCTS). The D1 defect has been explained as in its initial state, which has a tigthly bound hole and a loosely bound electron, pseudodonor. It is assumed to have important influence on device performance.

Another important defect that at the moment is subject to an extensive study, is the deep probably intrinsic defects that are seen in semi insulating Vanadium free SiC grown by HTCVD. The origin of the residual defects causing the semi-insulating behavior is not yet understood, but the presence of deeper states, labeled as UD1 and UD2, has been seen using FTIR spectroscopy.

We will also show results about lifetime limiting defects, which is an important parameter for bipolar devices. Special attention will be towards the influence of structural defects on the electrical properties such as the carrier lifetime.

Finally, we will describe the formation and properties of critical defects in high power SiC bipolar devices, under operation. We have shown that these phenomena are related to the generation of stacking faults in the SiC basal plane. This can be seen as a local reduction of the carrier lifetime, in triangular or rectangular shape, which explains the increased forward voltage drop in the diodes. The stacking faults and their associated partial dislocations are seen and identified using synchrotron topography. The entire stacking faults are also optically active as can be seen as dark triangles and rectangles in low temperature cathodeluminescence and as bright emitting features at higher temperatures. This defect is a critical defect for bipolar high power devices.

Opportunities and Technical Strategies for SiC Device Development

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The number of people worldwide working on SiC is small compared to the number working on silicon or GaAs, so our development efforts need to be *carefully focused.* We must identify devices and applications where SiC offers the greatest advantage, and where the technical and economic challenges are manageable. We must focus on *high value-added applications,* where SiC offers *system advantages* (such as high temperature operation) or capabilities not otherwise available in silicon or GaAs. We must be *innovative* in exploring new device structures and concepts to overcome the limitations of SiC materials. Finally, we must focus on material science issues that *really matter* to devices, and perform fundamental studies to resolve these issues. The most pressing materials, processing, and device design issues will be discussed in this presentation, and the current status of SiC power and microwave devices is summarized below.

POWER SWITCHING DEVICES

Virtually all SiC power MOSFETs developed to date are limited by the low MOS channel mobility, particularly on 4H-SiC. Recently, workers at Auburn and Vanderbilt Universities have shown that post-oxidation annealing in nitric oxide (NO) reduces the interface state density in the upper half of the bandgap by an order of magnitude, and increases the mobility dramatically [1, 2]. In addition, Fukuda et al. [3] have found that annealing in H_2 increases the mobility on the (11-20) surface of 4H-SiC to 110 cm^2/Vs.

UMOS vs. DMOS: which geometry is best? DMOS requires activation of p-type implants, resulting in poor surface morphology and lower channel mobility [4, 5], but the use of doped channels can mitigate this problem [6]. The inversion channel in UMOS devices is formed on a-axis surfaces exposed by RIE, where sidewall surface morphology is an issue, but recent results on un-etched planar (11-20) surfaces are very encouraging [3, 7]. Trench oxide breakdown in UMOSFETs can be overcome by the use of trench implants and current spreading layers [8]. The SIAFET mode of operation [9] is an intriguing innovation; look for more results later in this conference.

Enhancement-mode JFETs have recently been reported by workers at KEPCO and Cree [10]. These devices avoid the mobility and oxide reliability issues of MOSFETs, and exhibit attractive figures of merit, as shown in Fig. 1. Like JFETs, SiC BJTs avoid the critical MOS oxide issues and can operate at higher temperatures than MOSFETs. They are simpler to fabricate than MOSFETs, and are capable of higher current densities. However, they require substantial base current, which places demands on the drive circuitry. To minimize this, betas greater than 25-30 are needed. Cree has recently reported SiC BJTs [11] that substantially outperform the best SiC MOSFETs reported to date (see Fig. 1).

MICROWAVE DEVICES

SiC microwave MESFETs have demonstrated 120 W (pulsed) at 3.1 GHz with 41% PAE [12] and 5.2 W/mm at 3.5 GHz with 63 % PAE [13]. f_T of 22 GHz and f_{MAX} of 50 GHz have also been demonstrated [14]. Although these performance numbers are not as high as recently achieved with GaN HFETs, the relative simplicity of the SiC MESFET and the availability of a lattice matched substrate makes it an attractive device for many applications. Microwave SITs offer high power density in pulsed applications, but are restricted to low microwave frequencies (L to C band) [15, 16]. Recently, two groups have reported the first IMPATT diodes in SiC [17, 18]. Because of the high breakdown field, the pf^2 figure-of-merit for SiC IMPATT diodes is about 100x higher than either silicon or GaAs, and the small area makes IMPATTs ideal for an emerging material like SiC.

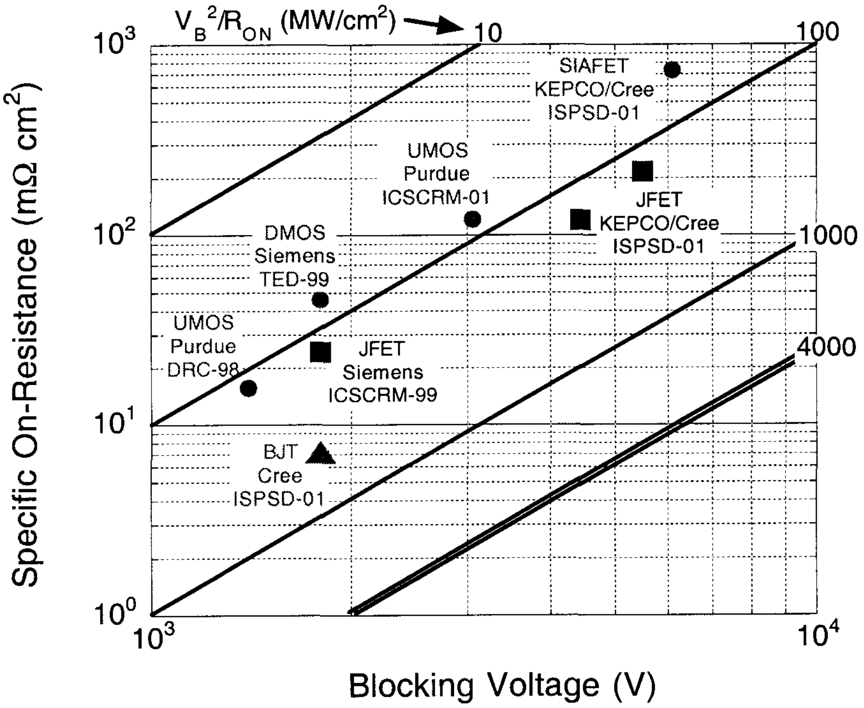

Figure. 1. On-resistance versus blocking voltage for several leading MOSFETs, JFETs, and BJTs. Diagonal lines are loci of constant figure-of-merit V_B^2/R_{ON}. The double diagonal line at 4000 MW/cm^2 is the theoretical limit for 4H-SiC unipolar devices. More results will be reported at this meeting. ***Use this chart to "pencil in" new data points as they are reported!***

Preparation of this paper was supported by grants N00014-01-1-0072 and N00014-01-0077 from the Office of Naval Research, and by the Indiana 21ST Century Research & Technology Fund.

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